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CALIBRATION OF THE AEDC-PWT AERODYNAMIC WIND TUNNEL (4T) USING DIFFUSER FLAP PLENUM SUCTION

J. A. Gunn

ARO, Inc.

April 1970

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NOTICES

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FOREWORD

The work reported herein was sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 65401F.

The calibration results presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, under Contract F40600-69-C-0001. The calibration was conducted on October 3 and 4, 1969, under ARO Project No. PC2044, and the manuscript was submitted for publication on February 16, 1970.

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This technical report has been reviewed and is approved.

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ABSTRACT

Tests were conducted in the Aerodynamic Wind Tunnel (4T) of the Propulsion Wind Tunnel Facility to determine the effectiveness of ejector flaps for plenum pumping. During the test, the Mach number was varied from 0.2 to 1.0, and the wall porosity was varied from 1.0 to 8.0 percent. The maximum Mach number attained when using flap plenum suction alone was slightly higher than 1.0. Choking which occurred at the flap hinge point prevented the attainment of higher Mach numbers. It was found that at each Mach number and porosity, a specific flap position will give a minimum centerline Mach number deviation, but for ease of operation, it is recommended that a flap position of 2.00 in. be set for all normal test conditions. The ejector flaps simplify the Tunnel 4T operation by reducing the number of control variables needed to set test conditions and also reduce the Tunnel 4T power requirements at some test conditions by as much as 19 percent.

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TABLE

APPENDIX
Illustrations

NOMENCLATURE

M_c	Equivalent plenum Mach number
$\overline{M}_S$	Average Mach number in test region from stations 72 to 100
M_∞	Average free-stream Mach number in test region from stations 72 to 140
p_c	Plenum pressure, psfa

p_e	Diffuser exit pressure, psfa
p_t	Stagnation pressure, psfa
δ_F	Diffuser flap opening, in.
δ_F^*	Diffuser flap opening which gives the best centerline Mach number distribution, in.
θ_w	Test section wall angle, deg (positive diverged)
λ	Tunnel pressure ratio, p_t/p_e
σ	Standard deviation
τ	Wall porosity, percent

SECTION I
INTRODUCTION

The Aerodynamic Wind Tunnel (4T) of the Propulsion Wind Tunnel Facility (PWT) is a continuous flow, closed-circuit, transonic wind tunnel which has a 4-ft square test section. The initial calibration of the tunnel, which has variable porosity test section walls, was completed in February, 1968, and the calibration results are reported in Ref. 1. Model studies of the Tunnel 4T walls (Refs. 2 and 3) indicated that modifications to the walls would improve the wave cancellation properties of the test section. The Tunnel 4T test section walls were modified, and in January, 1969, the tunnel was recalibrated. The results of this calibration are reported in Ref. 4.

Studies of the Tunnel 4T operating procedures indicated that plenum pumping provided with ejector flaps instead of auxiliary suction could, at times, simplify the process of setting Mach number in Tunnel 4T. Analysis also illustrated that the effective use of ejector flaps for plenum pumping would reduce the power required to operate the tunnel at some test conditions.

In order to verify the conclusions of the previous studies, the Tunnel 4T diffuser flaps were modified for use as ejector flaps. A complete calibration of centerline Mach number distribution as a function of flap position was made in addition to tests to determine the power reduction attained when flap suction was used. The results of the calibration and the power studies are presented in this report.

SECTION II
APPARATUS

2.1 BASIC TUNNEL

Tunnel 4T is a closed-loop, continuous flow tunnel with a usable Mach number range from 0.10 to approximately 1.35. The tunnel stagnation pressure can be varied from 160 to 3700 psfa. The stagnation temperature can be controlled only to a limited extent and ranges from approximately 80 to 130°F.

The test section flow is generated through a two-dimensional, fixed, sonic block nozzle with parallel sidewalls. Supersonic flow is generated by expansion through a 3-ft transition region between the nozzle and test section. The top and bottom test section walls may be converged or diverged 0.5 deg.

The model support system, located in the diffuser section, consists of a half-sector sting support with an angle-of-attack range from 28 to -12 deg with the pitch center located at station 108. A unique feature of Tunnel 4T is the Captive-Trajectory Store-Separation System (CTS). The system, which is described in Ref. 5, provides six degrees of freedom for model stores during trajectory analysis tests.

Tunnel 4T is normally powered by the second increment of the PWT Plenum Evacuation System (PES). The PES consists of two increments of compressors and an interconnecting ducting system which provides a high degree of versatility in the operation. For a large range of test conditions, Tunnel 4T can be run simultaneously with either of the PWT 16-ft tunnels.

The general arrangement of the PWT wind tunnel facility is shown in Fig. 1 (Appendix), and a more detailed layout of Tunnel 4T is provided in Fig. 2. A more complete description of Tunnel 4T and the other tunnels of PWT is given in Ref. 6.

2.2 TEST SECTION WALL GEOMETRY

The airside test section wall geometry is sketched in Fig. 3. The variable porosity feature, also illustrated in Fig. 3, is obtained utilizing a sliding cutoff plate behind the airside plate. The wall porosity, which can be changed during testing, ranges from 0- to 10-percent open area.

2.3 CALIBRATION EQUIPMENT

A centerline static pipe, which extended through the nozzle and test region, was used to determine centerline Mach number distributions. The pipe installation, which is illustrated in Fig. 4, is supported at its downstream end by the half-sector model support and at its upstream end by forward swept support struts attached to the nozzle sidewalls. A preload tension of 11,000 lb was applied to the pipe with spring washers at the forward support struts. Seventy-four orifices with 2-in. spacings are on the 2.875-in.-diam static pipe. Some static orifices were also located in the test section and diffuser walls.

All pressures were measured using the standard tunnel pressure system and 5-psid self-balancing transducers referenced to plenum pressure.

2.4 DIFFUSER FLAP SECTION

The flap section, located just downstream of the test section, has movable sidewalls and stationary top and bottom walls. The movable sidewalls allow adjustment of the wall positions to reduce flow blockage of the model support strut.

Normally the diffuser flaps are sealed with spring-loaded wiper seals bearing on wiper plates which are attached to the test section walls. For this calibration, the wiper plates and seals at the movable sidewalls were removed. The wiper plate was replaced with a seal strip, and the spring-loaded seal on the diffuser wall was replaced with a fairing. This modification changed the diffuser to an ejector-type plenum pump. The flaps can be adjusted during operation from a closed, sealed position to a maximum opening of about 6.5 in. Figure 5 is an illustration of the diffuser before and after modification.

SECTION III
PROCEDURE

3.1 TEST CONDITIONS

The calibration was conducted over the Mach number range from 0.2 to 1.0. The stagnation pressure (stilling chamber total pressure) was held at approximately 2000 psfa, and stagnation temperature was held at approximately 100°F.

3.2 DISCUSSION OF VARIABLES

The principal variables of interest during this investigation were as follows:

1. Free-stream Mach number, M_∞,
2. Wall porosity, τ, and
3. Ejector flap position, δ_F.

The distribution of local static pressure in the test section was obtained from measurements with a centerline probe, as explained in Section 2.3. The flow was assumed isentropic, and the tunnel stilling chamber total pressure was used to obtain Mach number. The test section Mach number, M_∞, is defined as the average of the local Mach numbers from stations 72 to 140.

The wave cancellation properties and the tunnel calibration are a function of the test section wall porosity, τ. During this test, data were obtained for wall porosities of 1, 2, 3, 4, 5, 6, and 8 percent.

In addition, the ejector flaps can be varied to change the Mach number distribution in the test section. For this test, the flap position, δ_F, was varied between the closed and the fully open position of 6.5 in. with the variation depending on the Mach number and porosity. Details of the ejector flaps are given in Section 2.4.

3.3 TEST PROCEDURE

When auxiliary plenum suction is used to set test conditions in Tunnel 4T, Mach number is adjusted with a combination of tunnel pressure ratio and plenum suction. However, when ejector suction is used, Mach number is controlled by the tunnel pressure ratio which adjusts the plenum pumping of the ejector flaps. The primary variables for this test, as stated in Section 3.2, were Mach number, flap position, and wall porosity. A wall porosity and flap position were set, and then, by changing the tunnel pressure ratio, the Mach number was adjusted to the desired nominal value using the appropriate ratio of plenum chamber pressure to stagnation pressure as determined from the previous calibration. Throughout this calibration, a wall porosity was set, and data were taken over the Mach number range, varying diffuser flap position at each Mach number.

In addition to a calibration of flap setting, special runs were made to determine the usefulness of the ejector flaps with the CTS installed and to determine the power reduction obtained using ejector flaps for plenum pumping instead of the normal auxiliary suction method.

One run was also made to find the maximum Mach number using both flap and auxiliary suction. For this run, the tunnel humidity was reduced to 0.0008 lb of water per pound of dry air. The only criterion for tunnel dryness during other runs was no visible condensation in the test section, which was monitored by television.

3.4 DATA REDUCTION

Mach number distribution data were obtained on-line using the PWT digital computer and data acquisition system. Local Mach numbers were calculated from the static pressure measurements and tabulated on the line printer. The data were also displayed on a cathode ray tube plotter as a function of tunnel station.

The average Mach number, M_∞, and the standard deviation, σ, were calculated for the 35 static orifices from stations 72 to 140. In addition to the free-stream Mach number, M_∞, an average Mach number for a short test region, $\overline{M}_S$, was calculated. The short test region, which was not usually affected by Mach number gradients which may occur at the rear of the test section, ranged from stations 72 to 100. The ratio of plenum pressure to stagnation pressure was used to calculate an equivalent plenum Mach number, M_c.

3.5 ACCURACY OF RESULTS

The uncertainties in the data which can be attributed to instrumentation errors and data acquisition techniques are presented below. The uncertainties were determined for a confidence level of 95.4 percent.

ΔM	± 0.002
$\Delta \tau$	± 0.02
$\Delta \lambda$	± 0.001
$\Delta p_c/p_t$	± 0.001
$\Delta \delta_F$	± 0.1

The precision in Mach number given above does not include the deviation from the mean value in the test region.

SECTION IV
DISCUSSION OF RESULTS

4.1 USE OF EJECTOR FLAPS

When Tunnel 4T is operated at $M_\infty \leq 1.0$ using auxiliary plenum suction, test conditions are set by the adjustment of two variables, p_c/p_t, and tunnel pressure ratio, λ. The calibration value of p_c/p_t

is used to set Mach number while the tunnel pressure ratio is set to give the best centerline Mach number distributions. Calibrations using long cone-cylinder models show that the pressure ratio affects the test section Mach number distribution gradient. A low pressure ratio will cause a drop in Mach number at the rear of the test section, while a high pressure ratio will have an opposite effect.

The need to control the two variables, p_c/p_t and λ, when using auxiliary suction complicates the Tunnel 4T operation because of interactions between the control systems. For example, if at a given Mach number p_c/p_t is high and λ is correct, an increase in auxiliary suction will lower p_c/p_t, but the pressure ratio will also decrease. When the pressure ratio is brought back to the original level, the control action will affect p_c/p_t and require another adjustment. Although the actual control of the tunnel under these conditions is not difficult, it is time consuming and detracts from the time available for data taking.

During the calibration, it was found that ejector flap plenum pumping simplifies the Tunnel 4T operation at $M_\infty \leq 1.0$. When the ejector flaps are used, the Mach number is obtained by setting the flaps at a fixed position and then increasing the tunnel pressure ratio until the calibration value of p_c/p_t is reached. Since the tunnel pressure ratio is no longer specified for each Mach number, it is not a control parameter, and only one control function is needed to obtain the desired Mach number. Test results which will be discussed later indicate that the test section Mach number distributions will be relatively free of gradients when the required value of p_c/p_t is set.

The Mach number limit reached in this test using ejector flap plenum suction only was approximately 1.05. This limit is apparently caused by flow choking at the ejector flap hinge point (Fig. 5).

4.2 FLAP CALIBRATION

As stated in the procedure, the method for obtaining data during this test was to set a wall porosity and Mach number and vary the opening of the ejector flaps. It was assumed that the Mach number distribution through the test region would be a function of flap opening and porosity. A quantitative evaluation of the uniformity of a Mach number distribution can be obtained by use of the statistical parameter, σ, the standard deviation. The standard deviation is approximately a root-mean-square quantity and actually measures the possible deviation of a variable from the mean of a given data set. A distribution band of $\pm 2\,\sigma$

with an associated confidence level of 95.4 percent was selected for use in this report to express the local Mach number deviation from stations 72 to 140.

Plots of the 2 σ Mach number deviation versus ejector flap deflection for a range of Mach number and wall porosities are given in Fig. 6. In most of these plots, minimum points or "buckets" indicate that at each Mach number and porosity there is an optimum flap setting which gives the best Mach number distribution. Generally, these optimum flap positions, δ_F^*, occur because the flap setting minimizes the "tail-off" or "tail-up" in the Mach number distribution at the end of the test region and gives longest usable test section. It can be seen in Fig. 6f, for example, that at M_∞ = 0.6 and τ = 6 percent, the minimum 2 σ is 0.0009 for δ_F^* of 1.90 in. A corresponding local Mach number distribution plot for each flap setting at M_∞ = 0.60 and τ = 6 percent is shown in Fig. 7, which illustrates the usefulness and sensitivity of the 2 σ parameter.

The flap settings which provide the best Mach number distributions through the Mach number range from 0.2 to 1.0 are given in Fig. 8 for porosities from 1.0 to 6.0 percent. This figure shows that the minimum δ_F^* openings of 1.2 in. at M_∞ = 0.2 and 2.5 in. at M_∞ = 1.0 occur at τ = 5 percent. In Fig. 9, the 2 σ deviations for the optimum flap position are given for each porosity. This plot indicates that like the flap opening, the lowest Mach number deviations are also found at 5.0-percent porosity. The 2 σ deviation at this porosity ranges from 0.0006 at M_∞ = 0.2 to 0.0022 at M_∞ = 1.0. These distributions are very good and compare with the other transonic tunnels at PWT which have 2 σ Mach number deviations from 0.004 to 0.005 at M_∞ = 1.0.

The local Mach number distributions for porosities of 1, 2, 3, 4, 5, 6, and 8 percent are displayed in Fig. 10. The data in this figure are given for the ejector flap positions which are approximately equal to the δ_F^* position given in Fig. 8 and which have the minimum 2 σ deviations shown in Fig. 9. It is interesting to note from these data that deviations usually occur in the last few inches of the test section except at τ = 8 percent, where a gradient exists through most of the test region.

The data in Fig. 6 indicate that a fairly large error in flap setting can be made without significantly affecting the distribution. For example, at M = 0.6 and τ = 5 percent, the flap setting can range from 1.00 to 2.0 in. with a maximum 2 σ deviation of 0.0022 over the entire test section length. A close inspection of the data indicates that the increased deviation from the optimum flap setting is caused by a Mach number gradient in the last 12 in. of the test section. Since very few models extend into this region, no problem will exist when the optimum flap schedule is not used. A constant flap setting for all porosities and Mach numbers will simplify the Tunnel 4T operation because operating time will not be spent adjusting flap positions. By considering the complete range of Mach number and porosities, it is suggested that a constant flap position of 2.00 in. will normally give a satisfactory Mach number distribution throughout the operating region. At 5-percent porosity, a 2.00-in. flap setting will give a maximum deviation of $2\sigma = 0.0023$. Long models should be tested at optimum flap positions. It is not necessary to close the flaps when auxiliary suction is used for supersonic Mach numbers.

Because of higher blockage and increased mass removal requirements, large model or CTS testing may require flap openings higher than 2.00 in. The flaps may be opened as much as necessary to set test conditions under these circumstances.

4.3 POWER SAVINGS USING FLAP SUCTION

Before this calibration, the normal method of Tunnel 4T operation was to use the PES Units D and E to drive the tunnel and F Unit for auxiliary plenum suction. One phase of this test was to compare the power consumed using flap and auxiliary suction. Test conditions of $M_\infty = 0.6$ and 0.9 at a pressure level of 1960 psfa were held for the power comparison test. At each Mach number, auxiliary suction was used, and the power on D, E, and F Units was recorded. The F Unit was put on standby, and the power of the D and E Units was recorded after test conditions were reestablished using flap suction. The conditions were also repeated using F Unit in parallel with D and E to drive the tunnel. A summary of the test conditions and results is given in Table I.

TABLE I
SUMMARY OF POWER REDUCTION TEST RESULTS

PES Config.	Mach Number	p_{t_a}, psfa	δ_F, in.	Auxiliary Suction	PES Power, MW				MW/psf
					D Unit	E Unit	F Unit	Total	
2-14	0.6	1950	1.50	No	15.0	16.0		31.0	0.0159
2-14 + F	0.6	1958	Closed	Yes	15.0	15.5	8.4	38.9	0.0199
2-15	0.6	1958	1.50	No	14.0	14.5	8.0	36.5	0.0186
2-14	0.9	1950	1.75	No	16.5	17.5		34.0	0.0174
2-14 + F	0.9	1950	Closed	Yes	16.5	17.1	8.4	42.0	0.0215
2-15	0.9	1960	1.75	No	14.9	15.5	8.6	39.0	0.0199

In this table, the column headed "PES Config." provides standard nomenclature used at PWT. The first number denotes the PES increment being used, the second the number of compressor stages, and the third the number of compressors in the first stage. For example, in Table I a 2-14 configuration number indicates that Tunnel 4T is being driven by four, one-stage (i.e., parallel) compressors from the second increment of PES. The Ⓕ implies that F Unit is used for plenum suction. It should also be noted that Units D and E are each dual compressors, and F Unit is a single compressor.

The results of this test show that the flap suction provides the minimum power usage. At $M_\infty = 0.90$, the 2-14 configuration (D and E Units driving the tunnel with no flap suction) gives a power to stagnation pressure ratio of 0.0174 MW/psf while the 2-14 + Ⓕ configuration gives a ratio of 0.0215 MW/psf. The power using flap suction is, therefore, 19 percent lower. The 2-15 configuration consumes more total power than the 2-14 configuration but allows a lower power level on the individual units. When D and E Units are fully loaded in 2-14 (27.5 mw each) at a given stagnation pressure, a configuration change to 2-15 will lower the power on D and E, and the stagnation pressure can be raised until the machines are again fully loaded. This type of operation is advantageous because for one increment operation in the range from $M_\infty = 0.5$ to 1.0, the maximum stagnation pressure, which is machine-power limited, can be raised by approximately 250 psfa.

4.4 MAXIMUM MACH NUMBER USING BOTH FLAP AND AUXILIARY SUCTION

One run was made at $\tau = 8$ percent to determine the maximum Mach number which can be obtained in Tunnel 4T. Data were taken with the flaps closed and with the maximum auxiliary suction available. The Mach number obtained at this test condition was 1.39. By opening the flaps to a maximum position and retaining the maximum auxiliary suction, a Mach number of 1.42 was reached. The 2 σ deviation for these data is 0.0426, and in general, the resulting high gradients make testing at this Mach number unsuitable.

4.5 VERIFICATION OF PREVIOUS CALIBRATION DATA

The method for obtaining a calibration of the relation between the equivalent plenum Mach number, M_C, and the test section Mach number, M_∞, is explained in Ref. 4. In general, the test section Mach number is a function of M_C, porosity, and wall angle. The relation between these parameters can be reduced to a hypersurface fit of the data. In Fig. 11, data from the Ref. 4 calibration and the hypersurface fit developed from these data are compared with the flap calibration data for δ_F^*. (The flap suction calibration data are almost independent of flap setting so that $(M_\infty - M_C)\ \delta_F \approx (M_\infty - M_\infty)\ \delta_F^*$.) The agreement is quite good, although the hypersurface curve generally gives values slightly higher than the flap calibration data. This difference can be attributed to the fact that the Ref. 4 test did not cover the complete Mach number-porosity schedule in the subsonic range, and therefore, only a limited amount of data was available for obtaining the hypersurface curve fit. At 3- and 6-percent porosities where the Ref. 4 data are complete, the hypersurface fit is more accurate and correlates better with the flap calibration data than at porosities where no Ref. 4 data were taken.

SECTION V
CONCLUSIONS

Based on the results from this calibration of Tunnel 4T, the following conclusions have been reached.

1. The use of diffuser flaps removes the necessity to control the tunnel pressure ratio at $M_\infty = 1.0$ and lower. This simplifies the tunnel operation by eliminating one control variable.

2. With a sonic nozzle and using only the ejector flaps for plenum pumping, the maximum Mach number attainable in Tunnel 4T is approximately 1.05.

3. For each Mach number and porosity, an optimum flap setting, δ_F^*, is obtained, which gives a minimum deviation in the centerline Mach number distribution.

4. At the optimum flap position, δ_F^*, the minimum centerline Mach number deviation occurs at 5-percent porosity. The $2\,\sigma$ deviation at this porosity varies from 0.0006 at $M_\infty = 0.2$ to 0.0022 at $M_\infty = 1.0$.

5. Since only the last few inches of the centerline distribution are affected by operation with δ_F not equal to δ_F^*, the flaps can normally be set at 2.00 in. for all Mach numbers and porosities without affecting model data.

6. The use of diffuser flaps can at some test conditions reduce the power required to operate Tunnel 4T by 19 percent and increase the maximum stagnation pressure for one increment PES operation by 250 psfa in the Mach number range from 0.5 to 1.0.
7. The maximum Mach number obtainable in Tunnel 4T using a combination of ejector flaps and auxiliary suction is 1.42.
8. The calibration of Tunnel 4T as determined in previous tests was verified during this calibration.

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APPENDIX
ILLUSTRATIONS

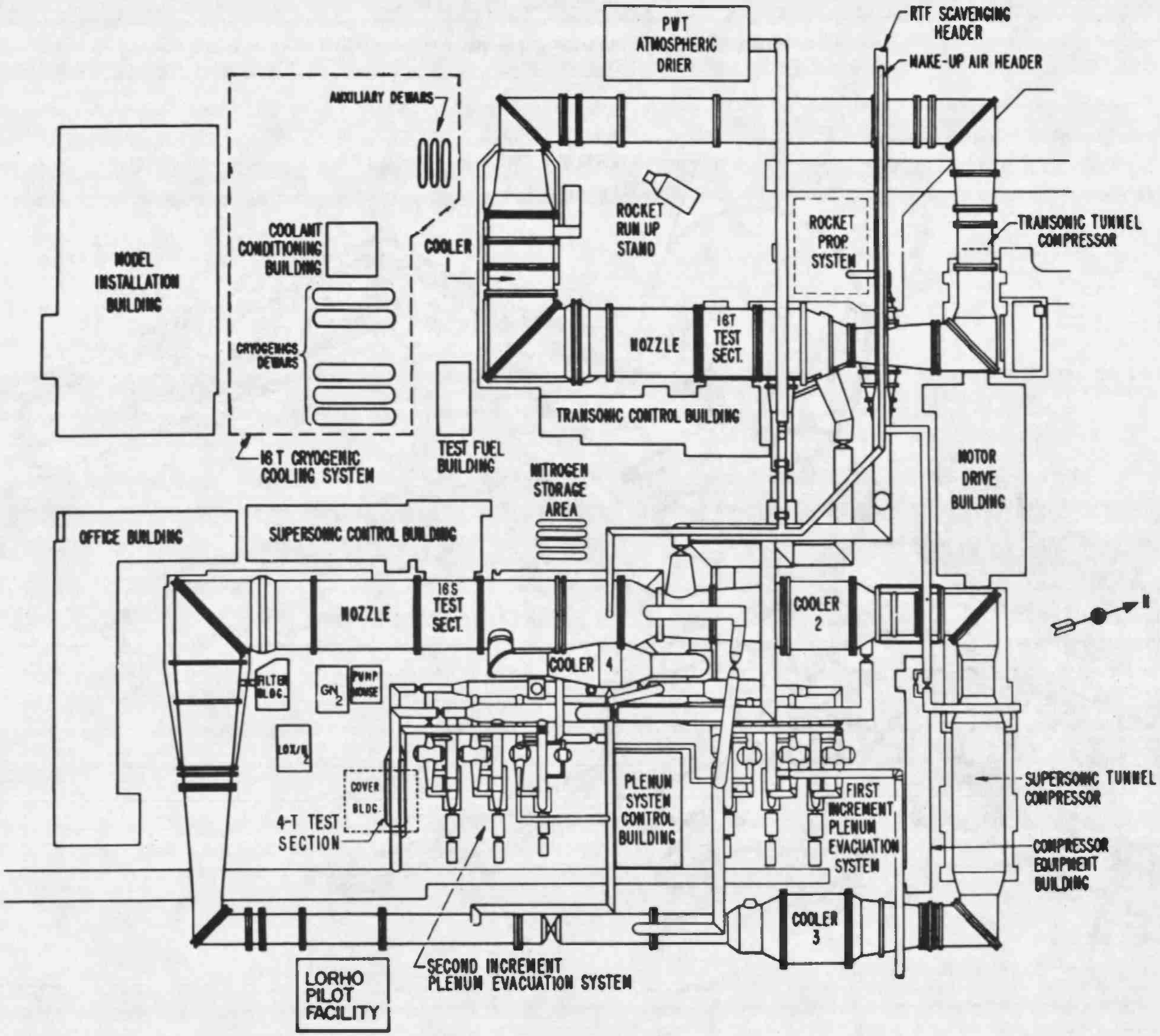


Fig. 1 Propulsion Wind Tunnel Facility

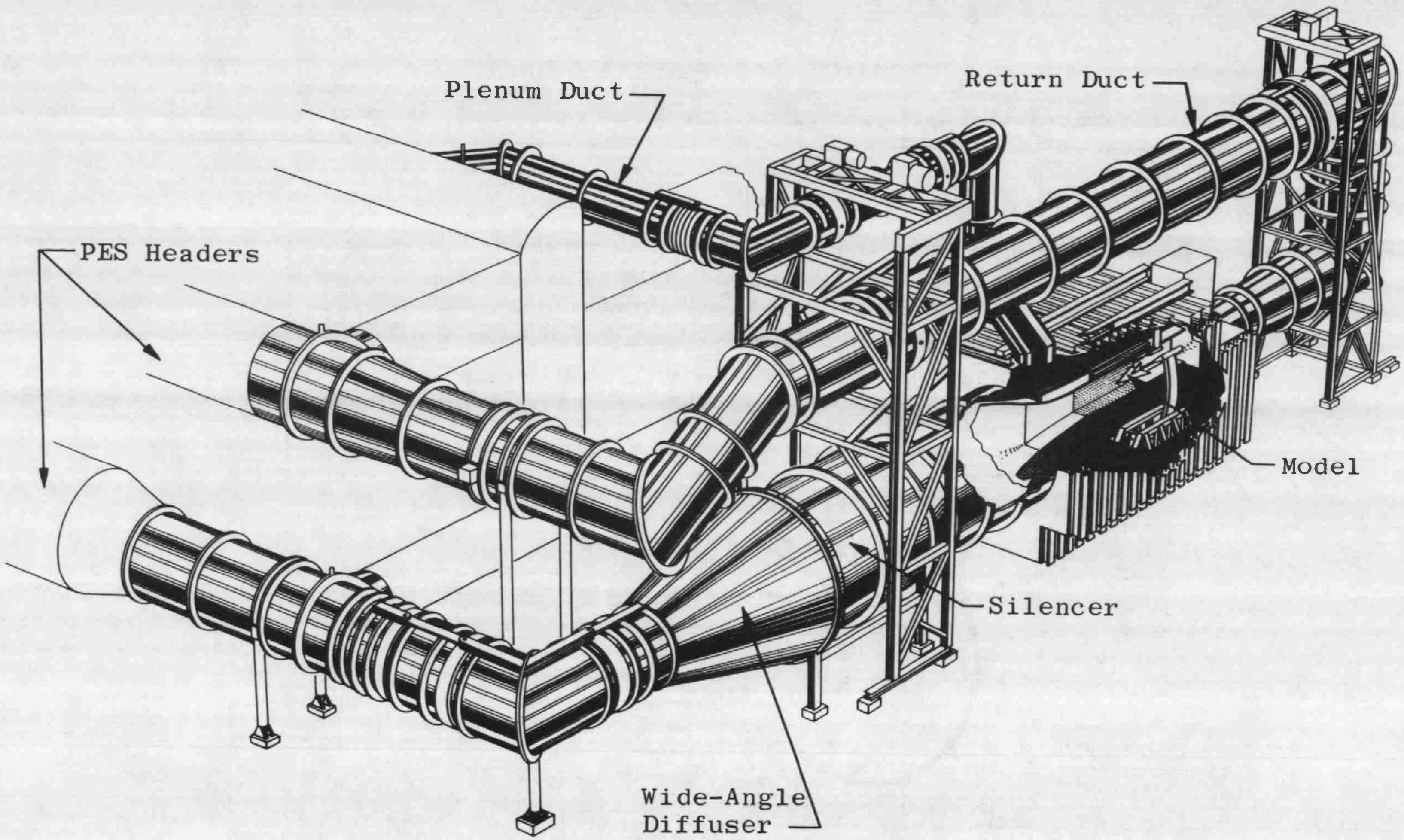


Fig. 2 Tunnel 4T General Arrangement

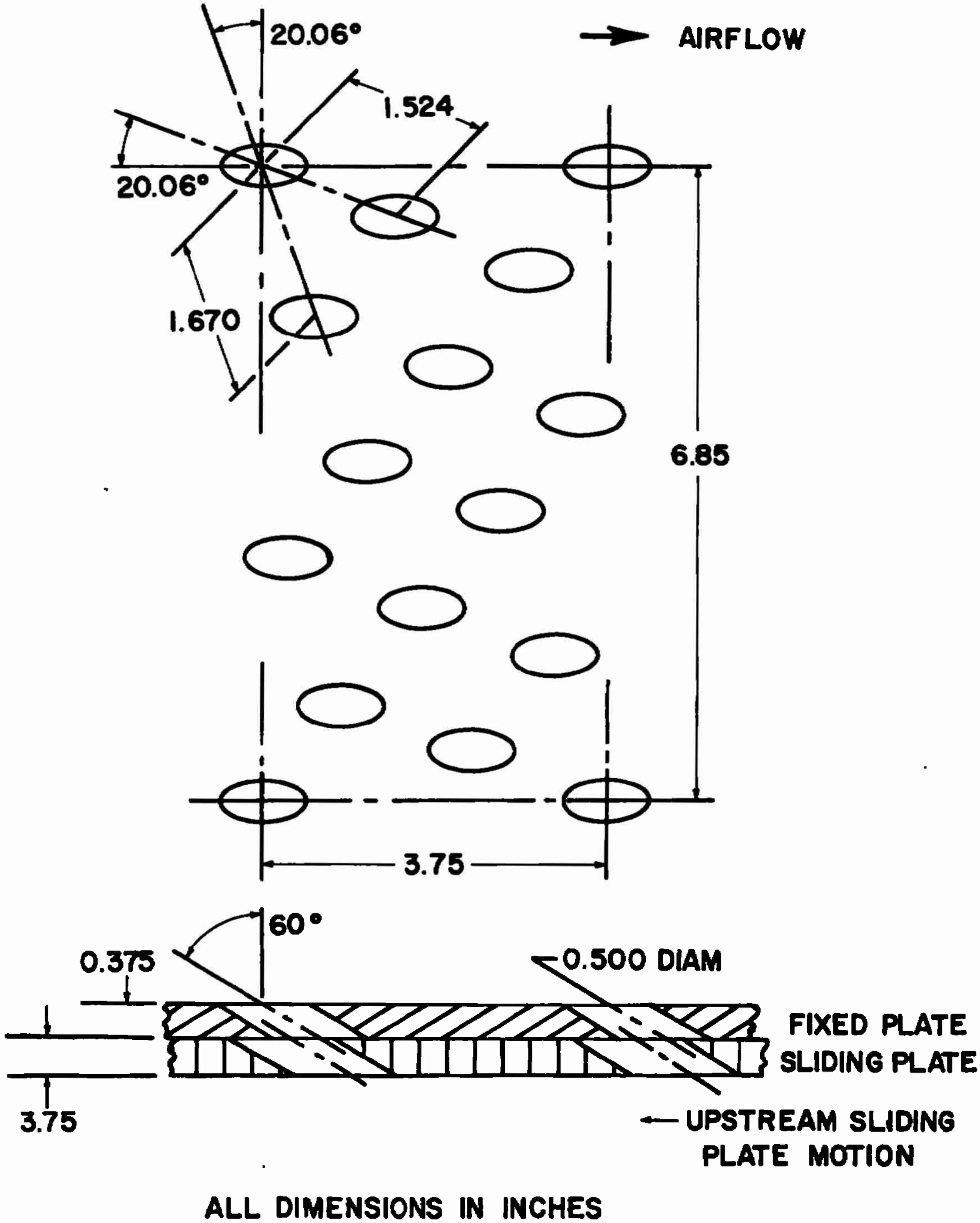


Fig. 3 Airside Test Section Wall Geometry

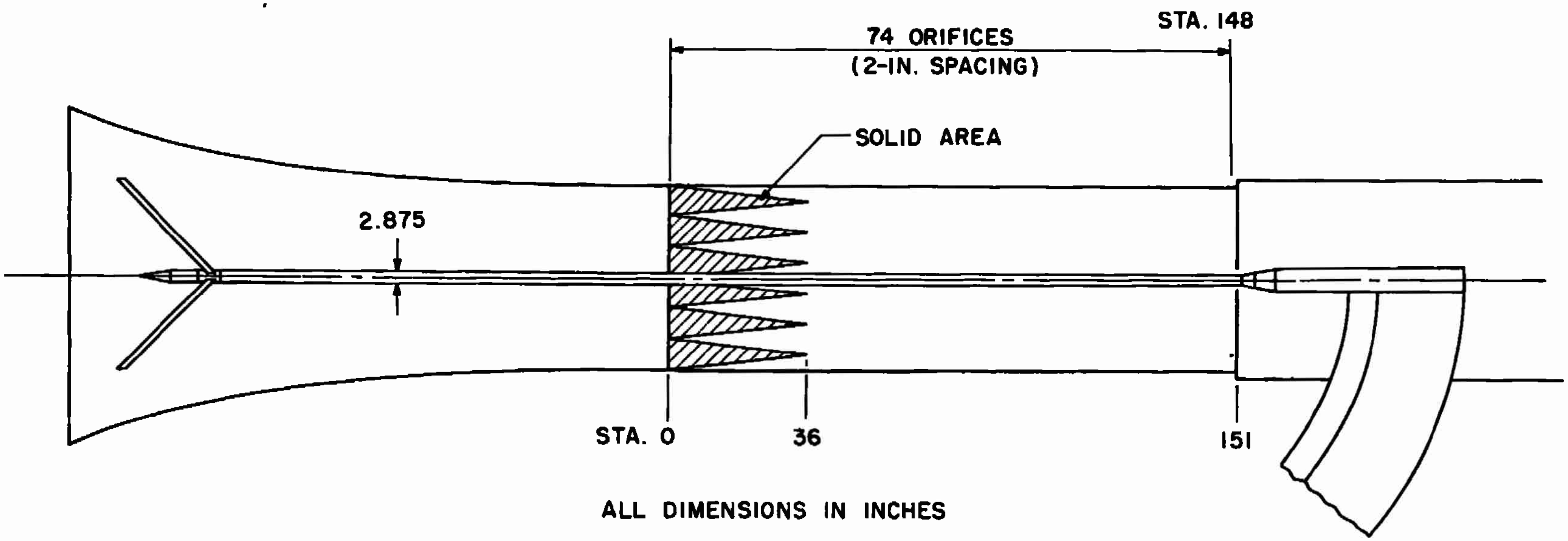


Fig. 4 Centerline Static Pipe Installation

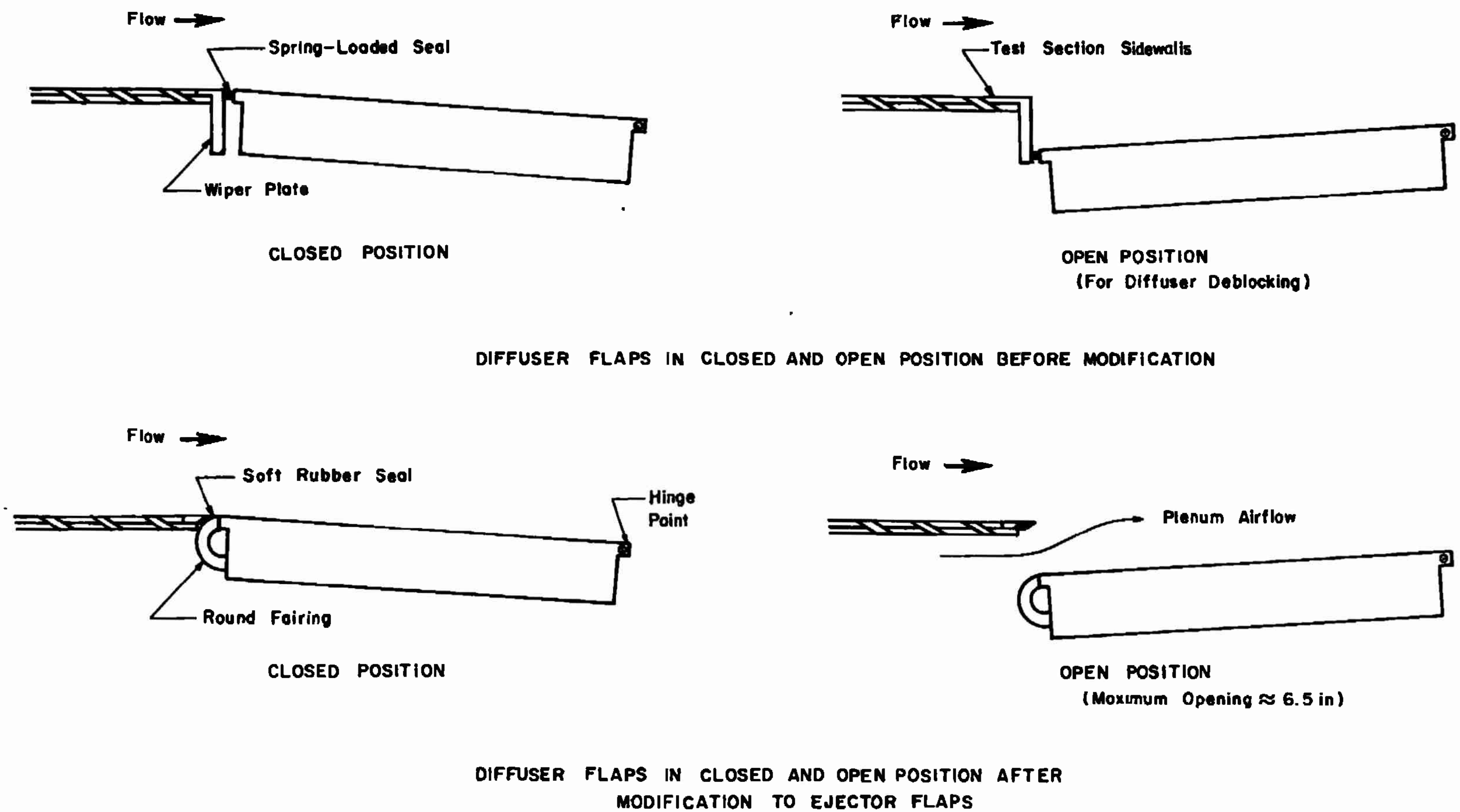
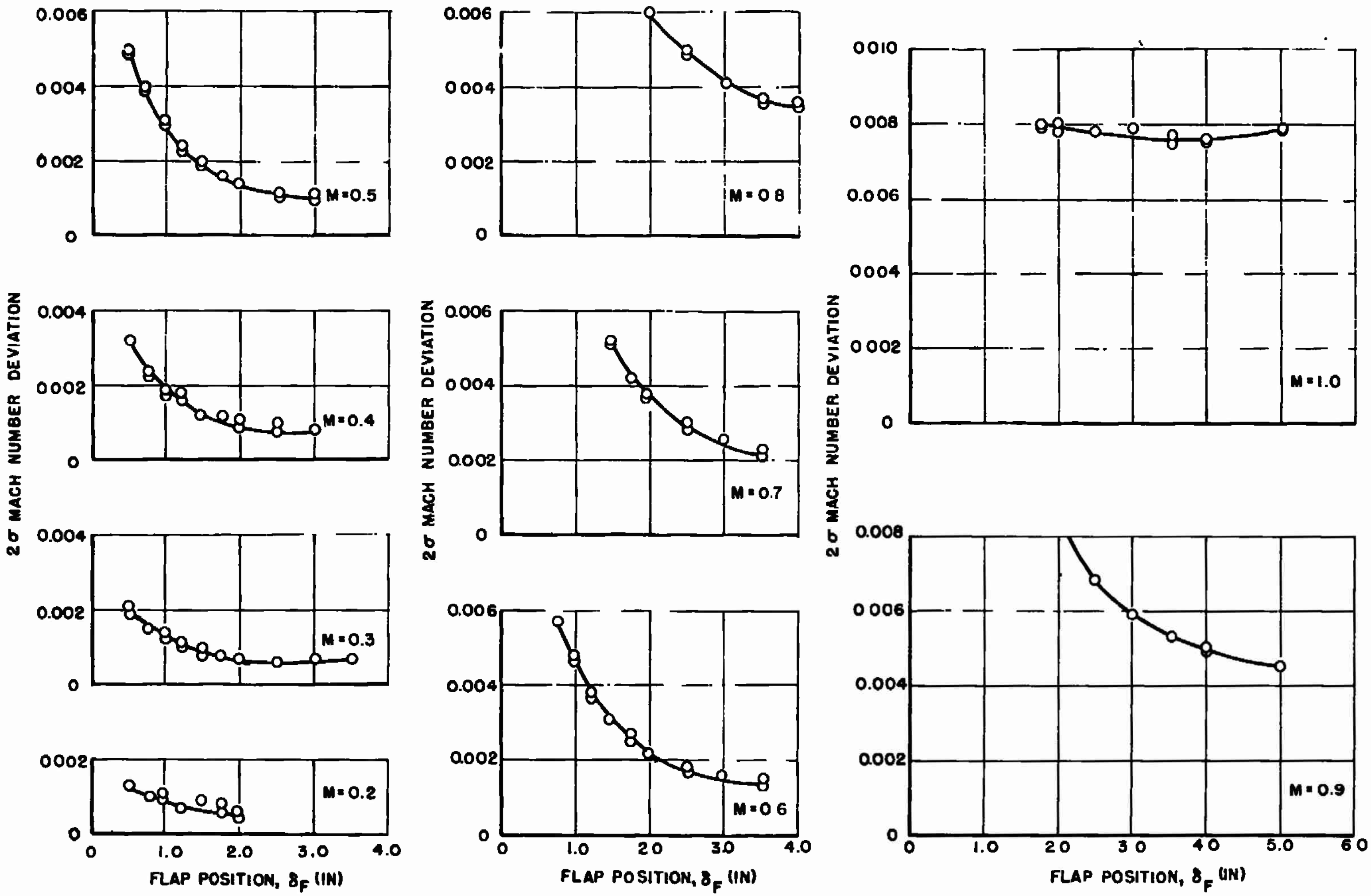
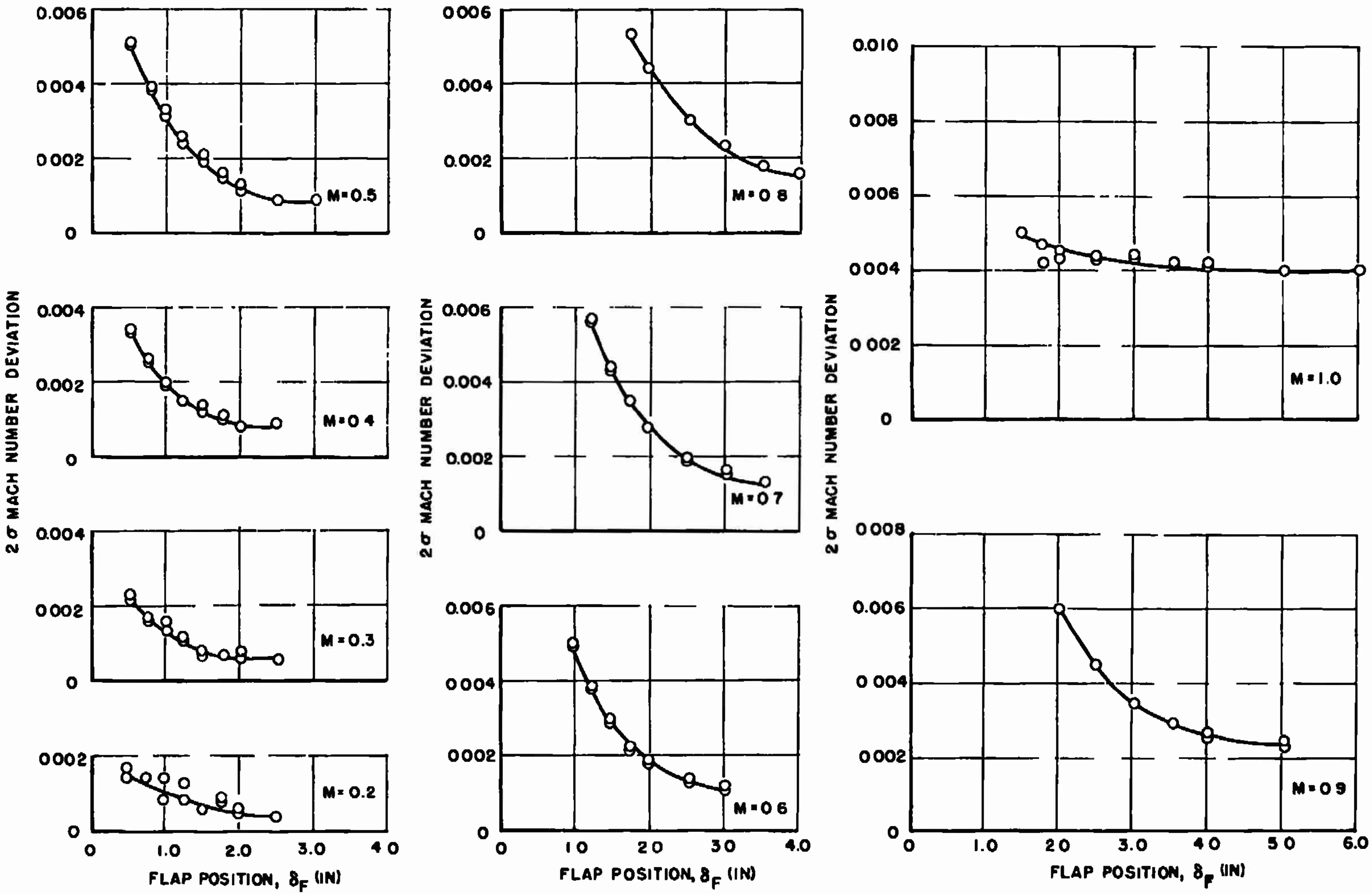


Fig. 5 Tunnel 4T Diffuser Flaps

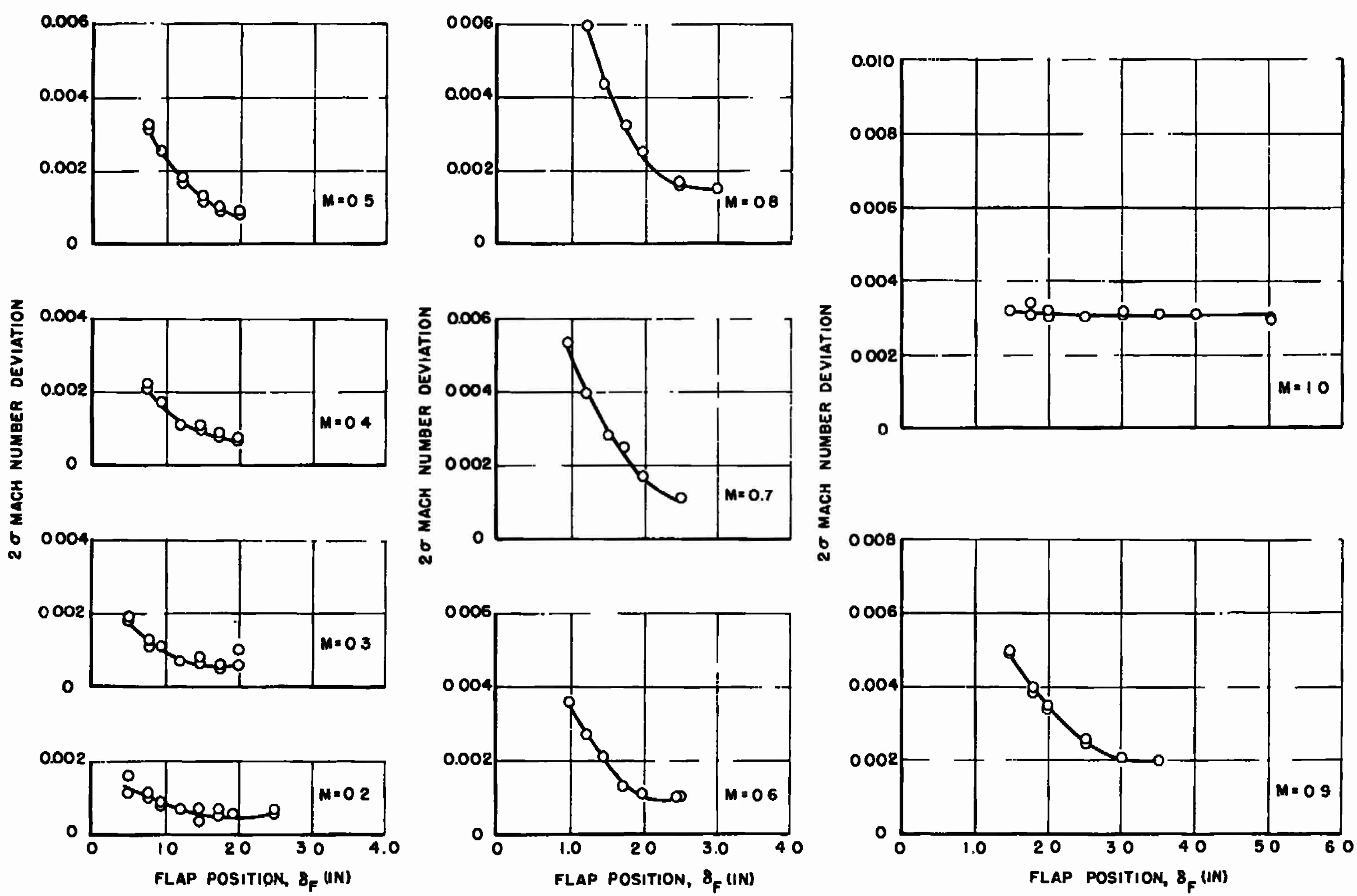


a. τ = 1 Percent

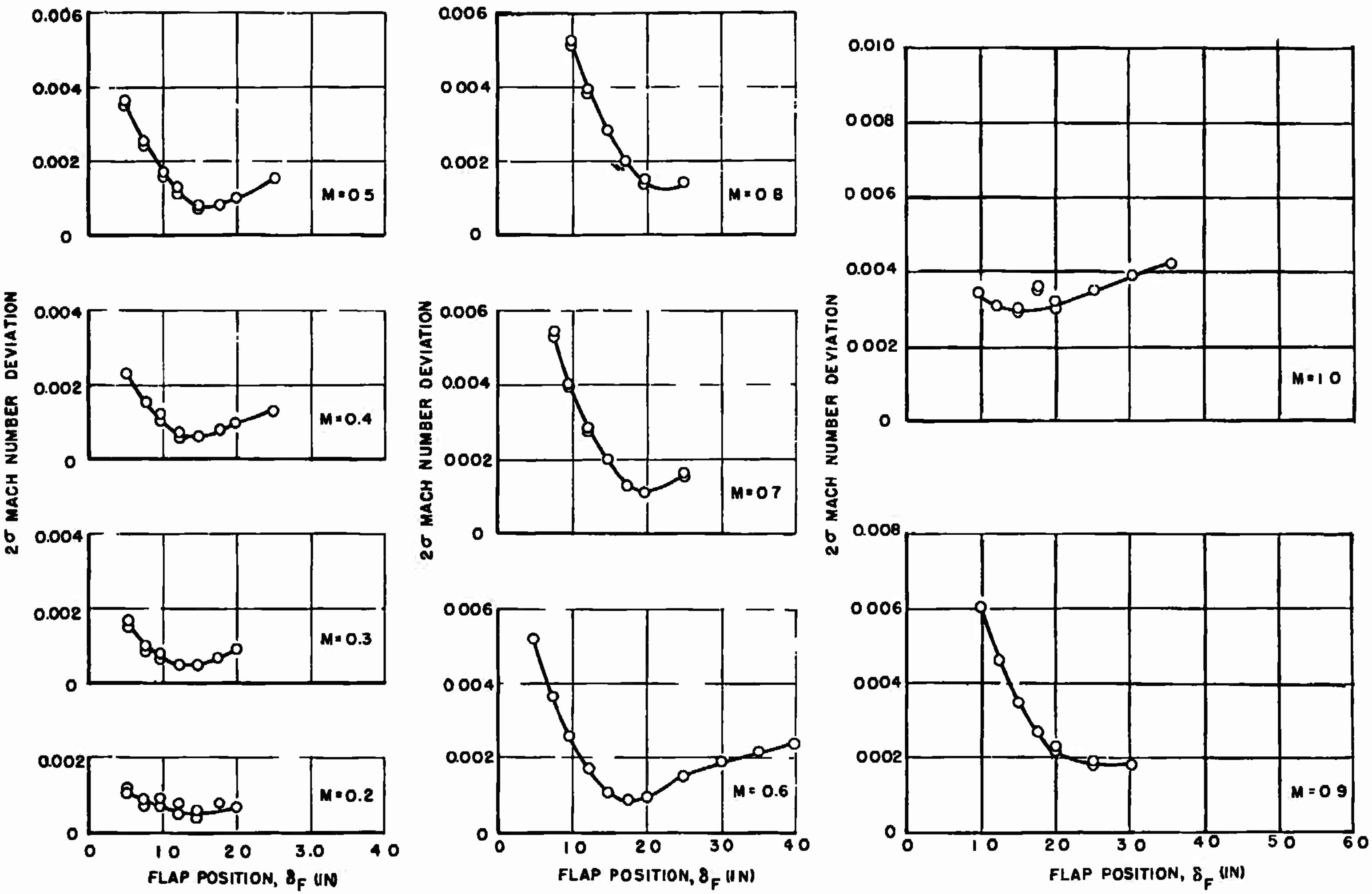
Fig. 6 Variation of 2 σ Mach Number Deviation with Flap Position, Mach Number, and Wall Porosity



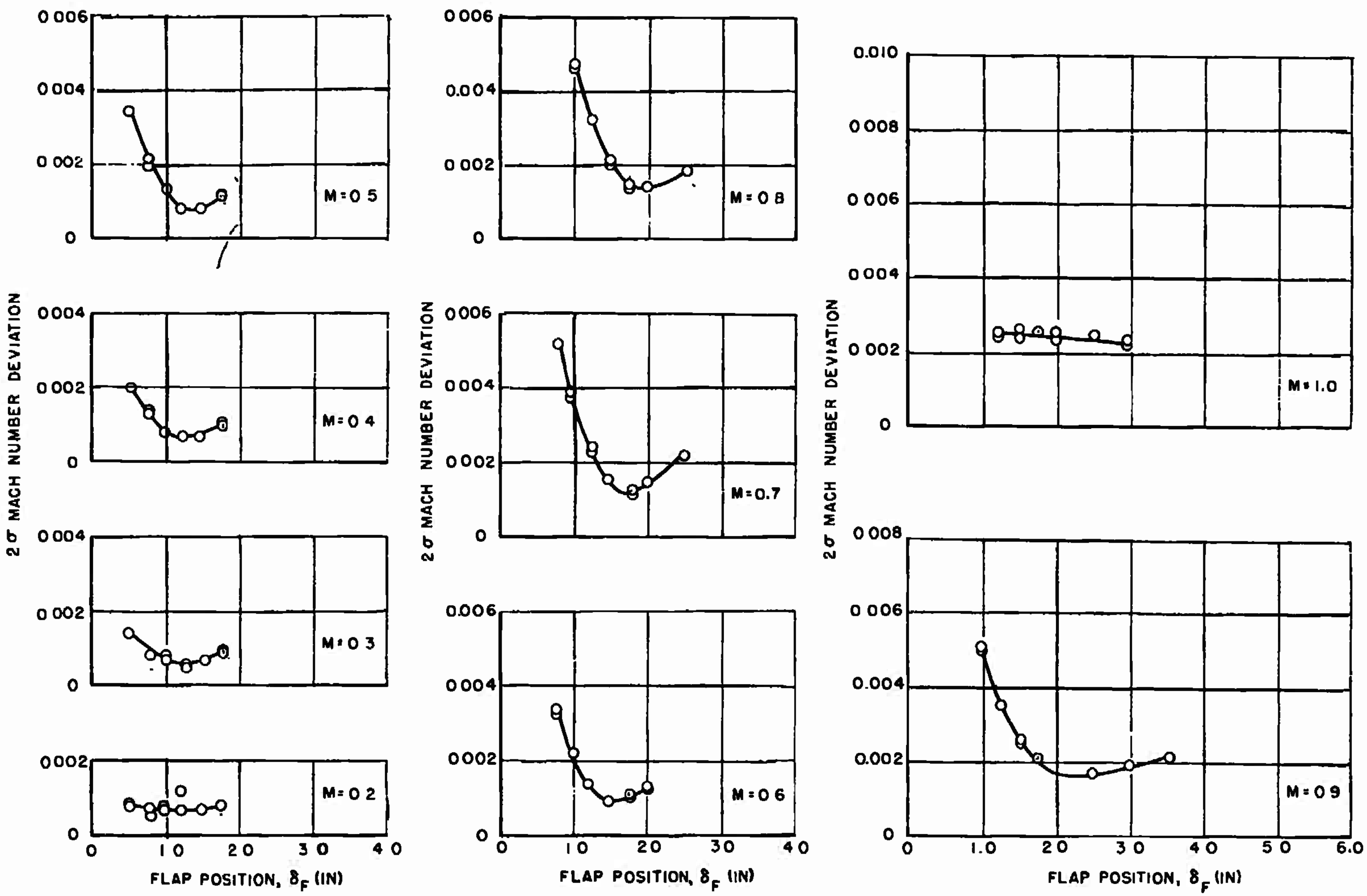
b. τ = 2 Percent
Fig. 6 Continued



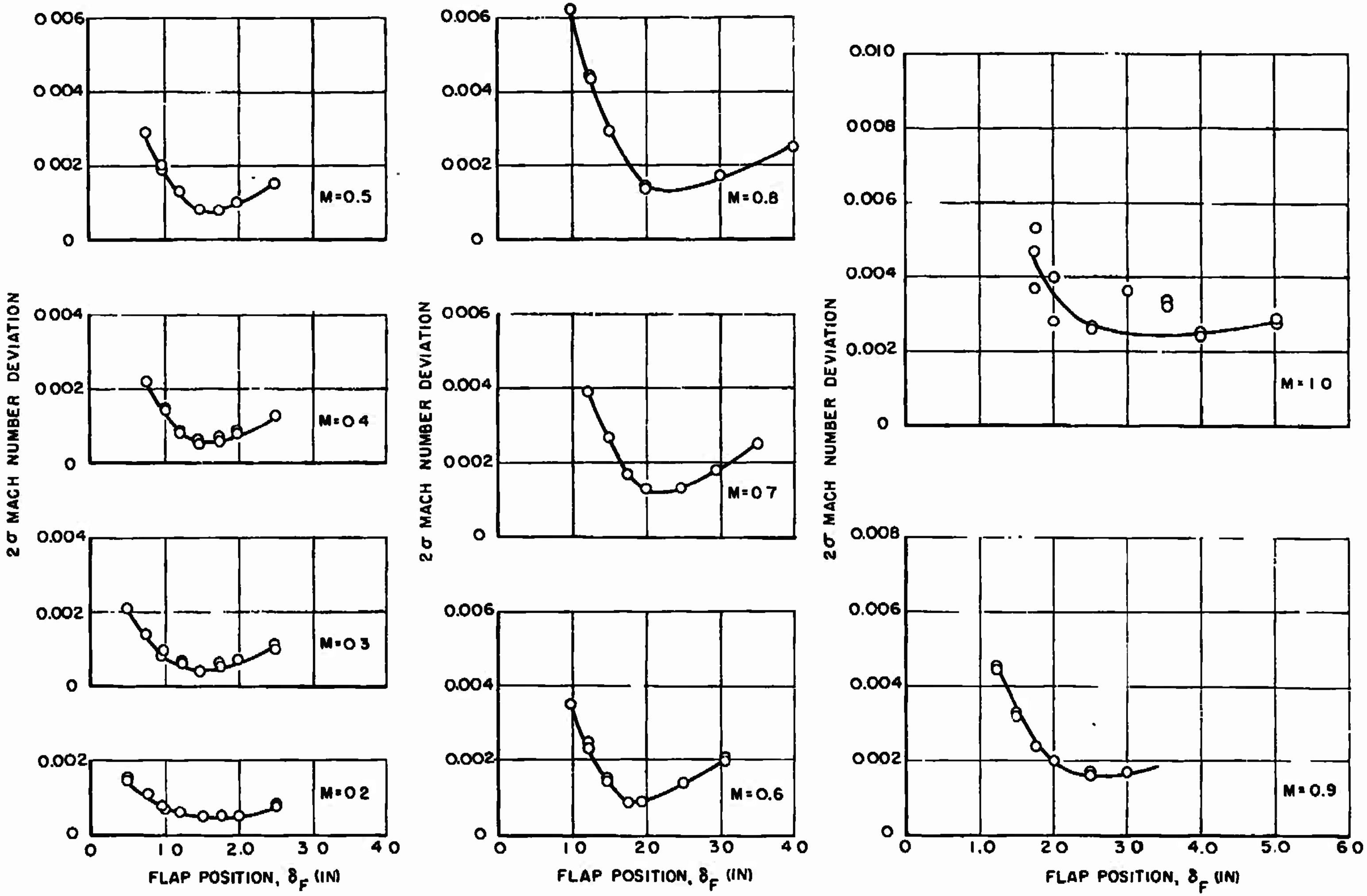
c. τ = 3 Percent
Fig. 6 Continued



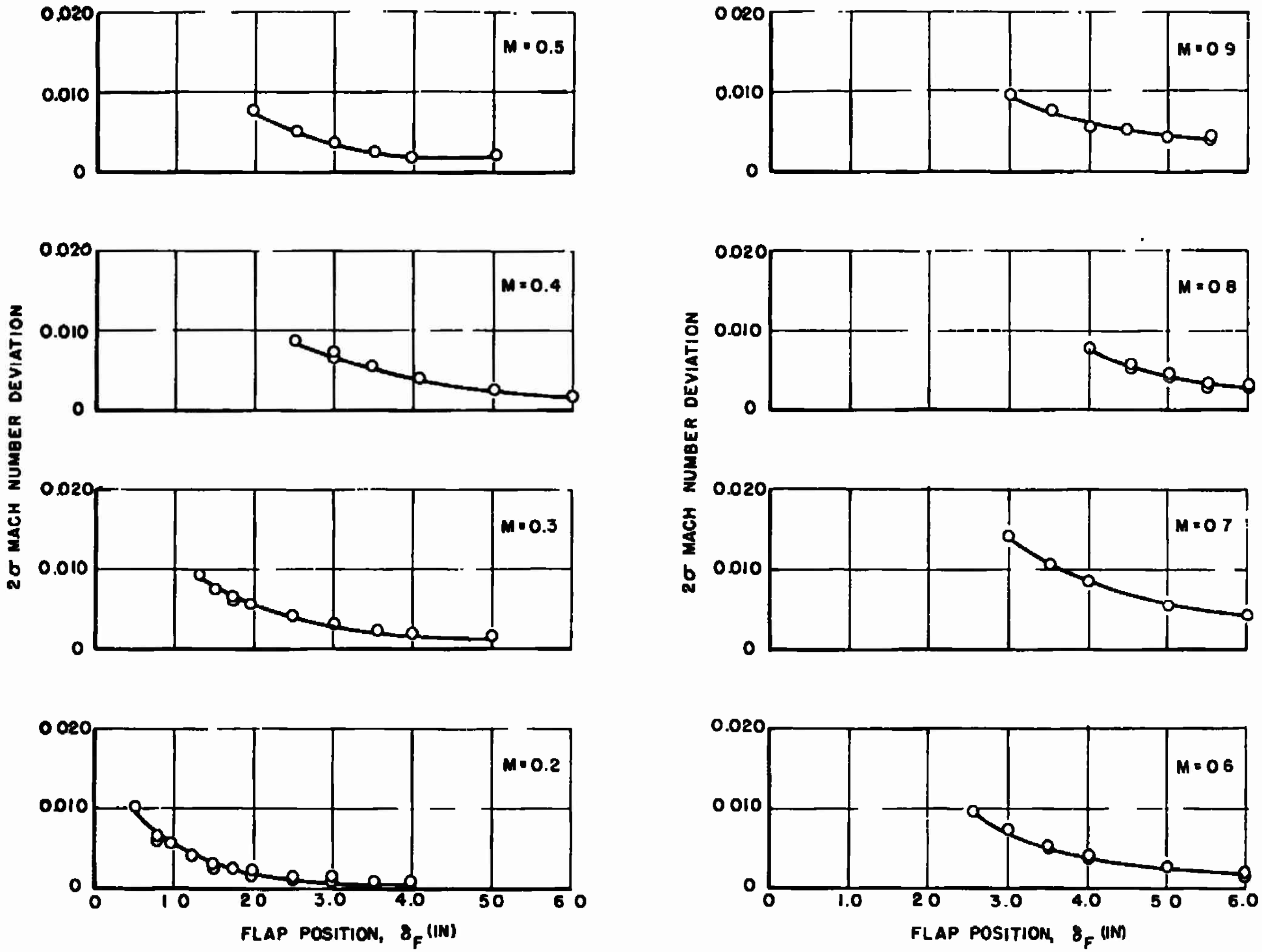
d. τ = 4 Percent
Fig. 6 Continued



e. τ = 5 Percent
Fig. 6 Continued



f. τ = 6 Percent
Fig. 6 Continued



g. τ = 8 Percent
Fig. 6 Concluded

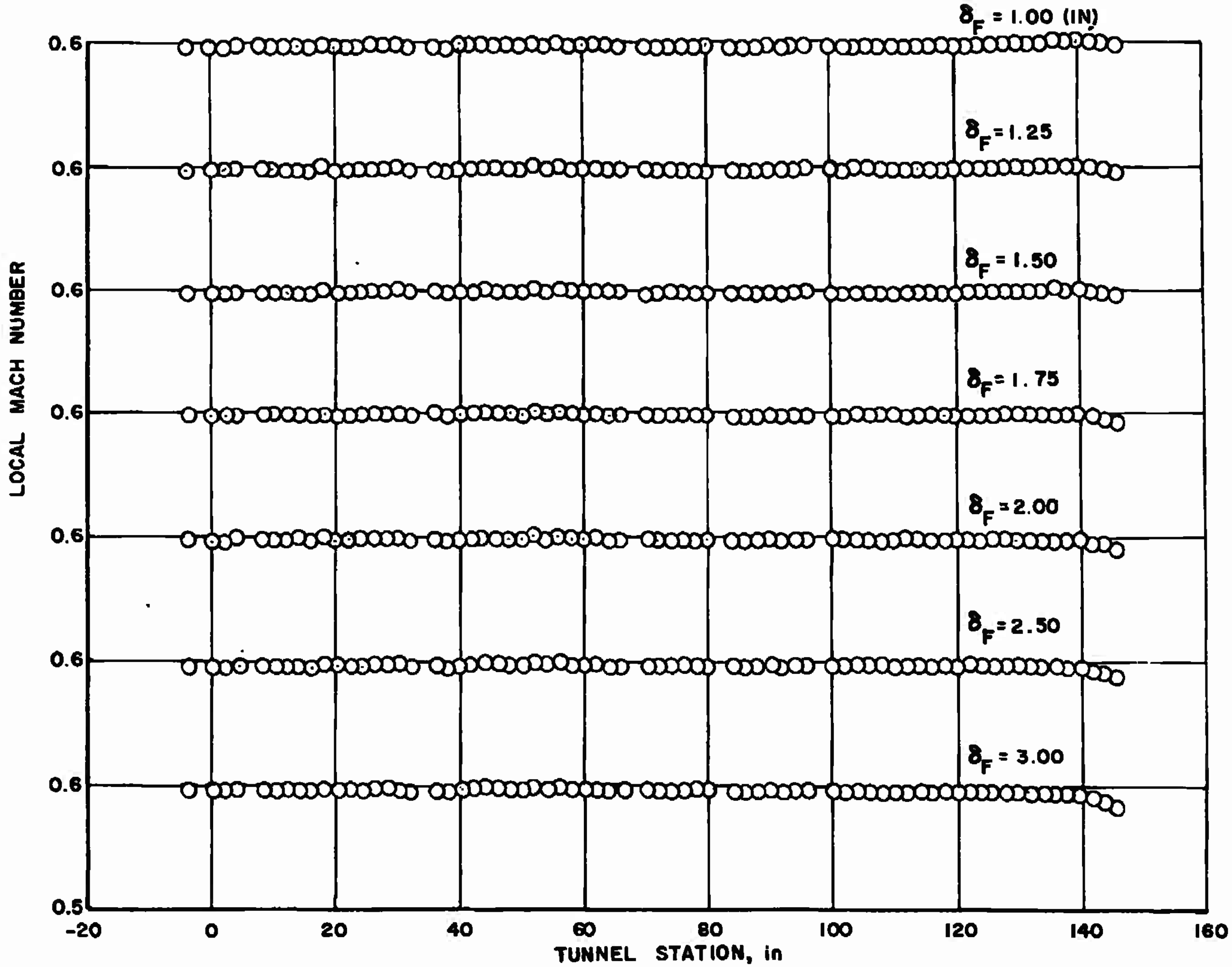


Fig. 7 Effect of Flap Position on Local Mach Number Distribution at M_∞ = 0.6 and τ = 6 Percent

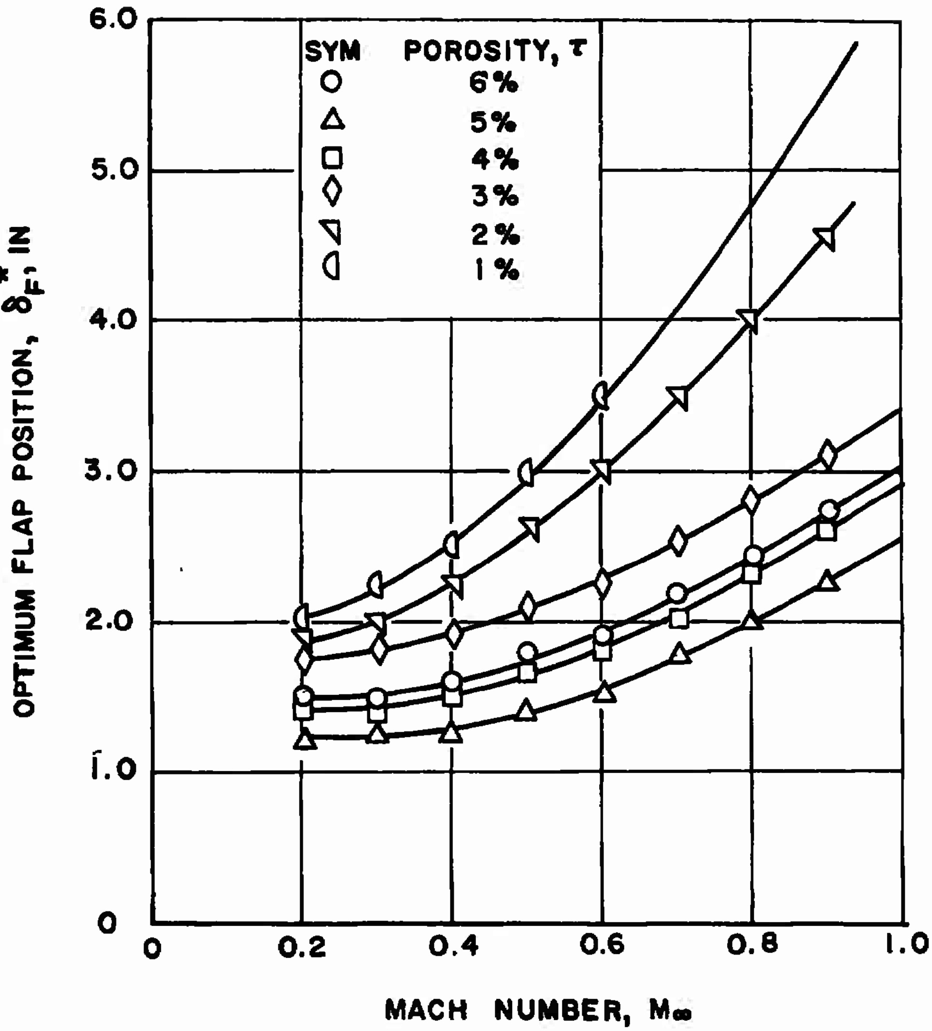


Fig. 8 Variation of Optimum Flap Position with Mach Number

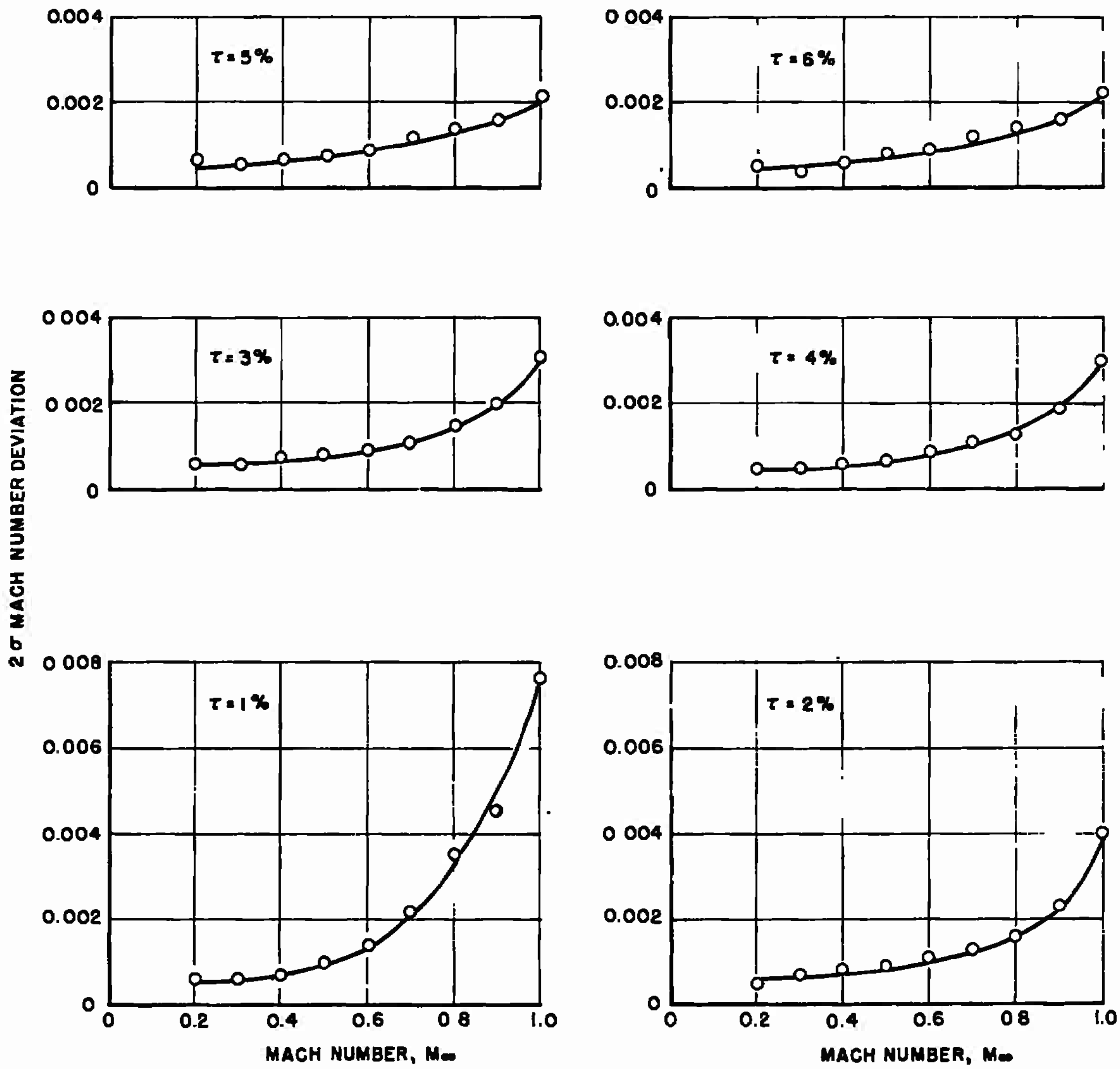
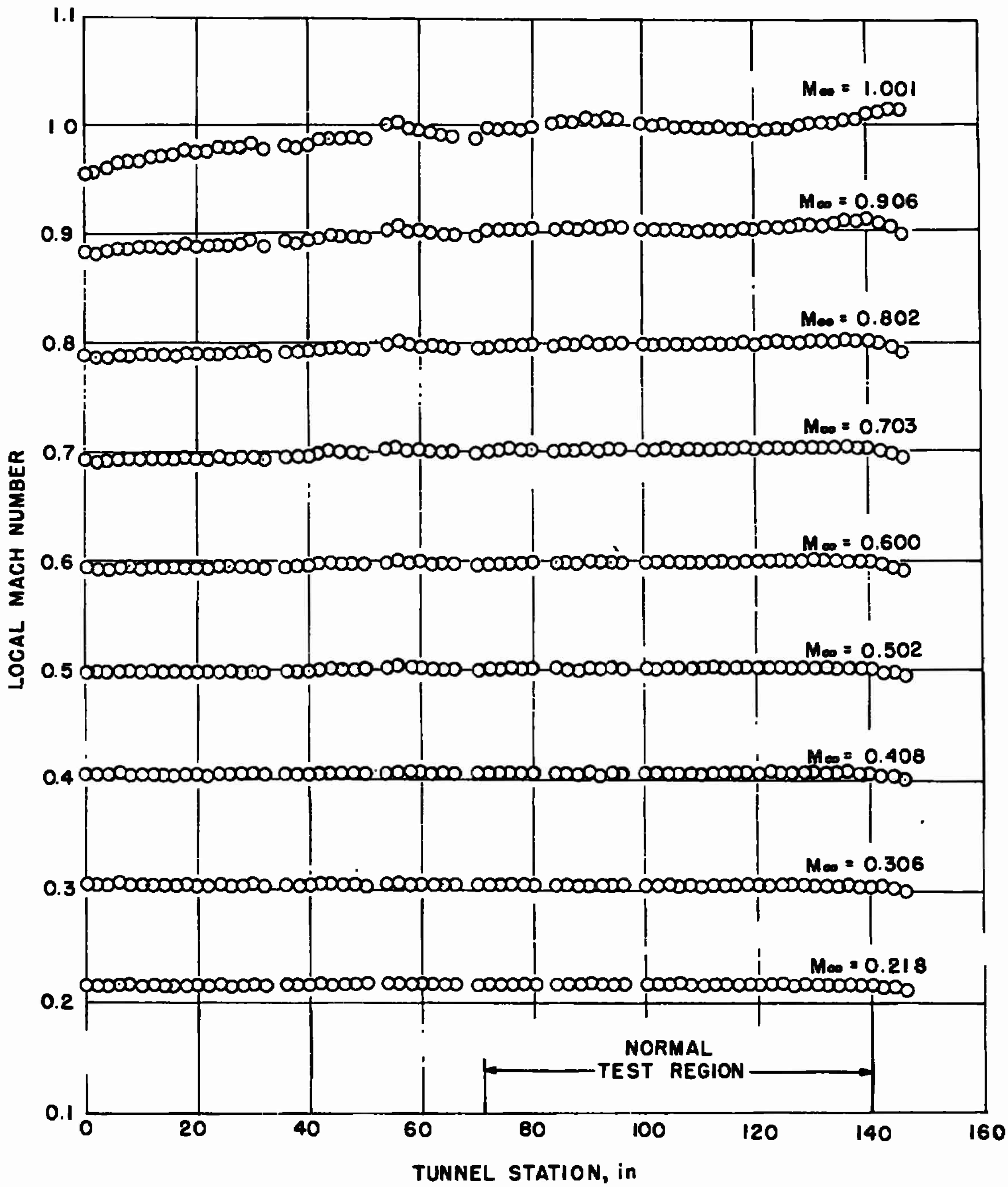
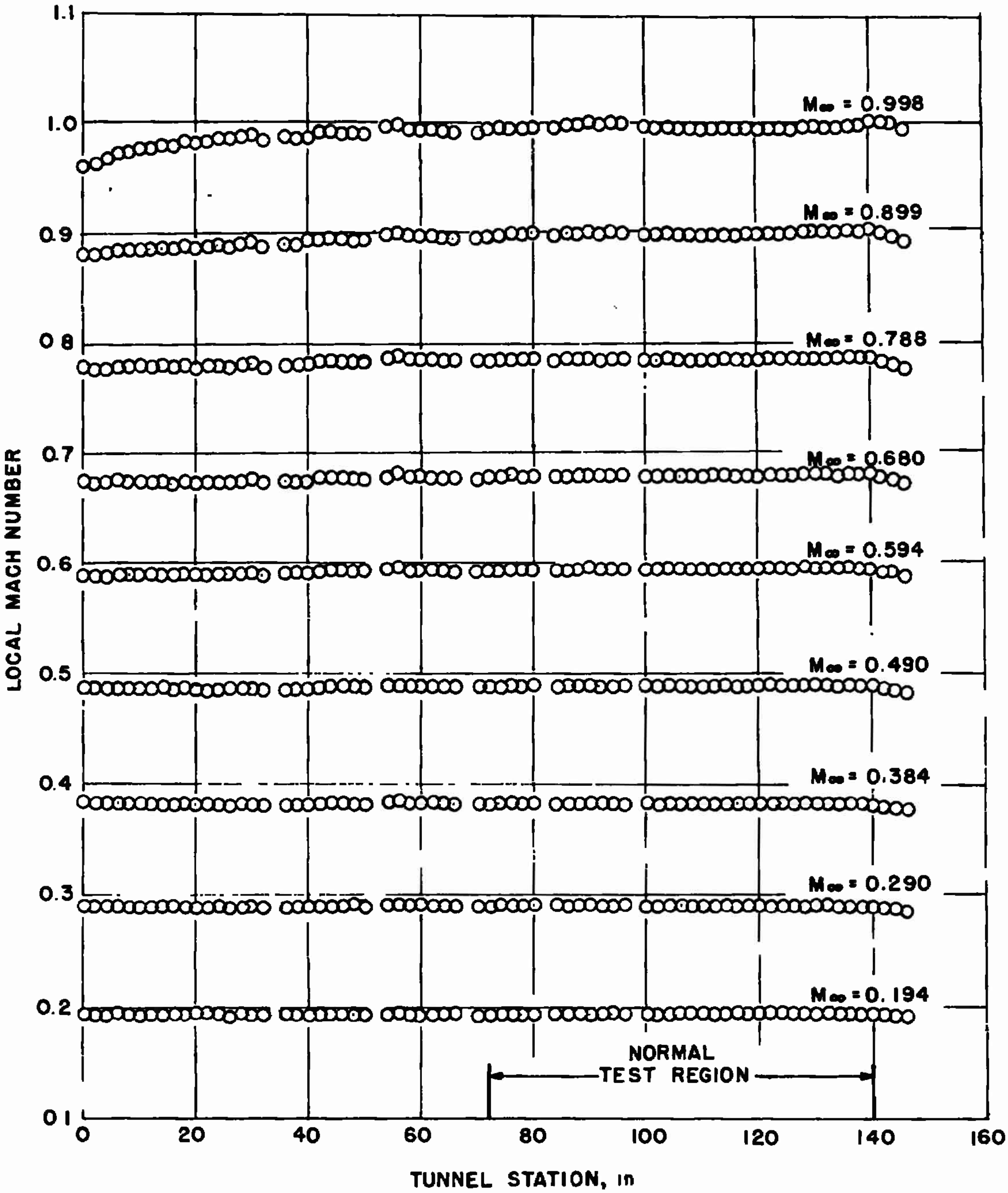


Fig. 9 Variation of 2 σ Mach Number Deviation with Mach Number for Optimum Diffuser Flap Positions

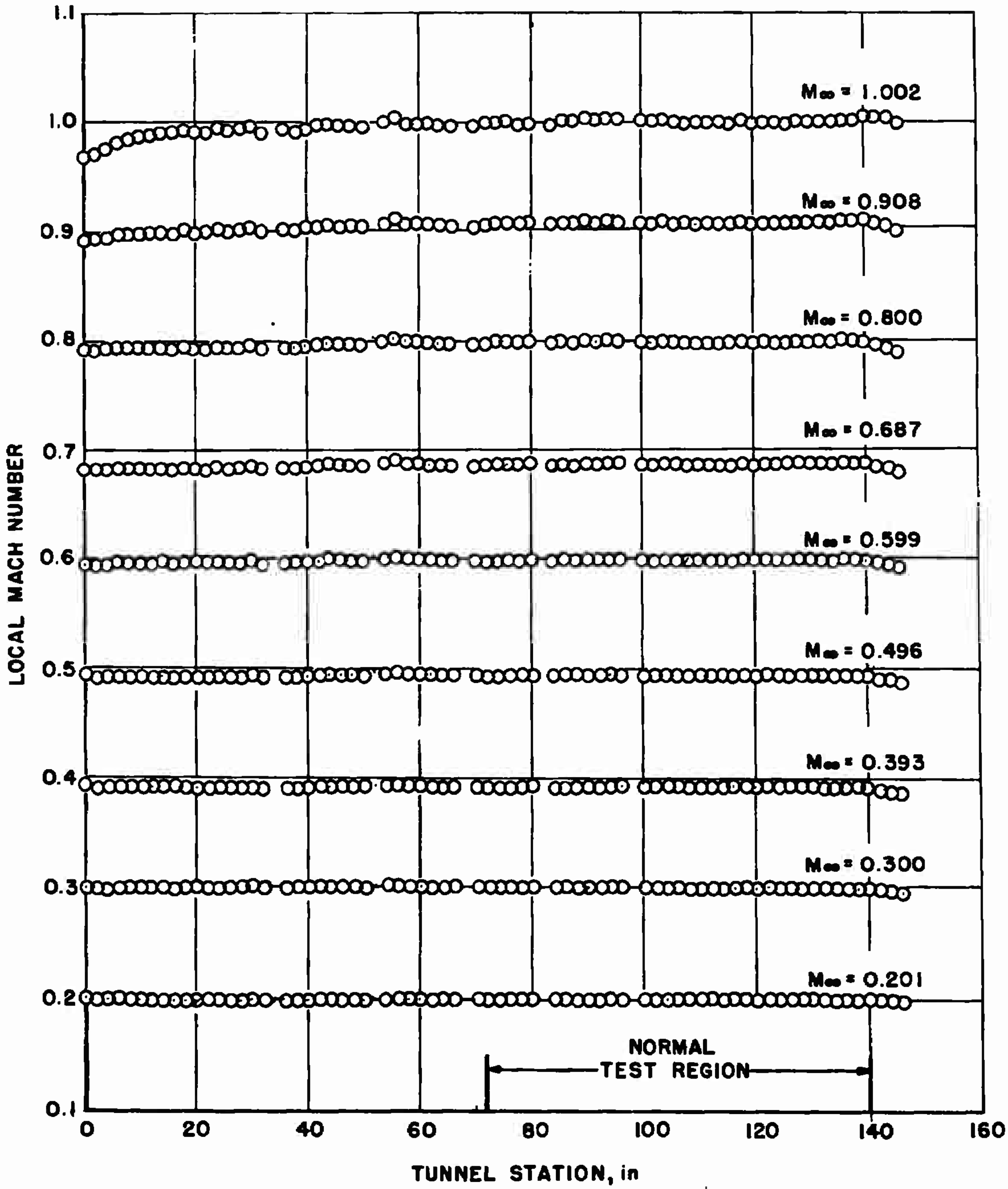


a. τ = 1 Percent

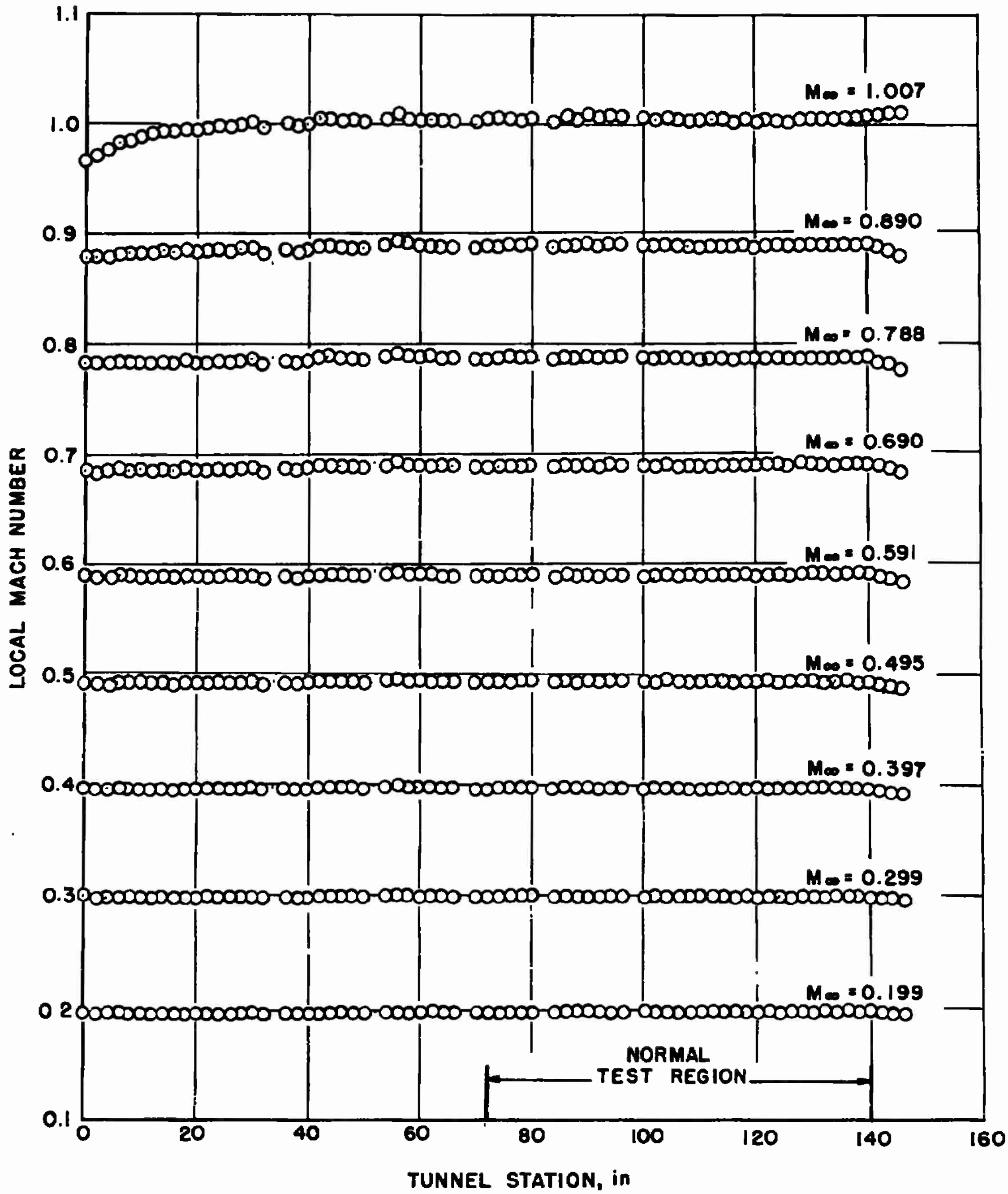
Fig. 10 Centerline Mach Number Distributions for Optimum Diffuser Flap Positions



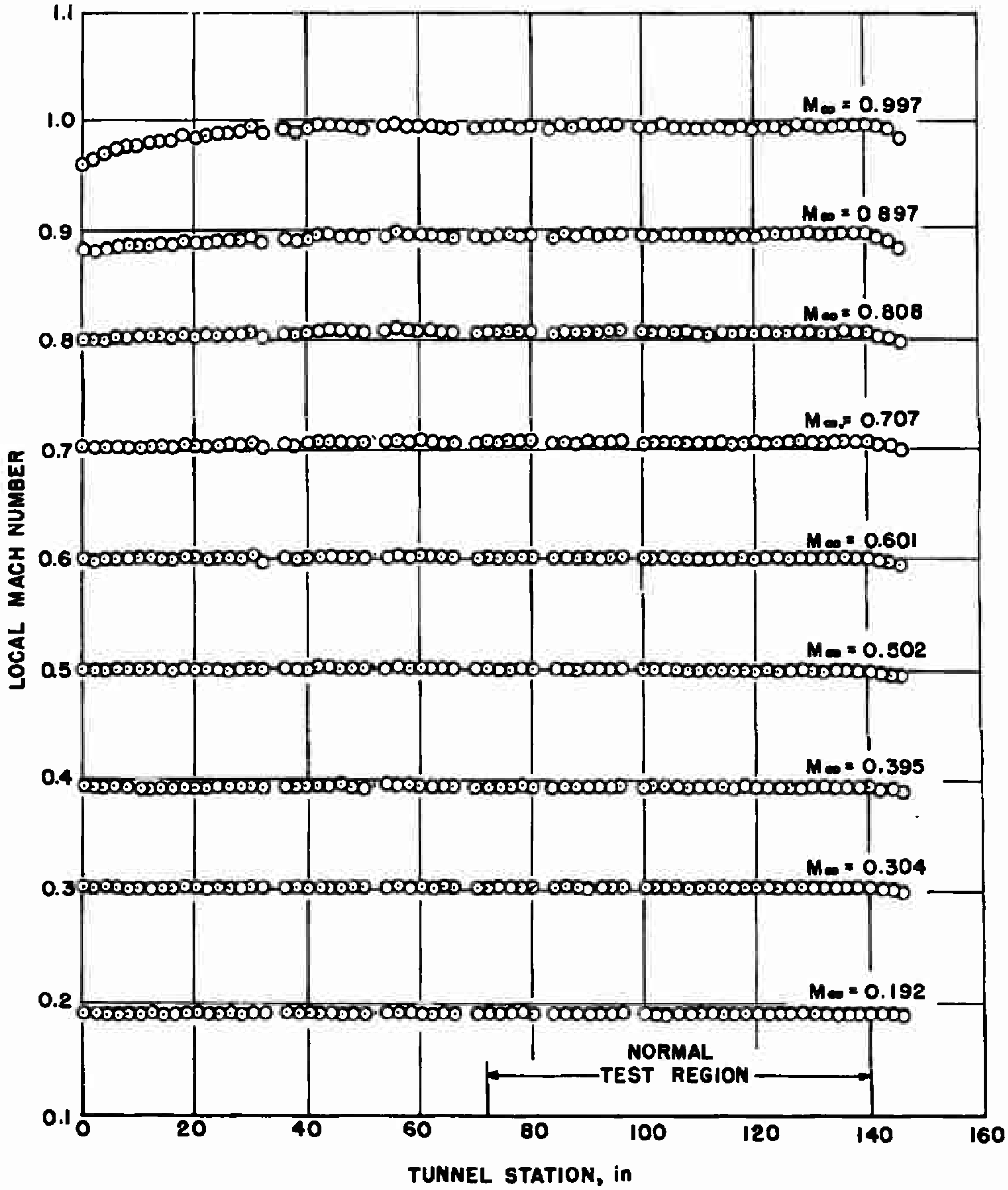
b. τ = 2 Percent
Fig. 10 Continued



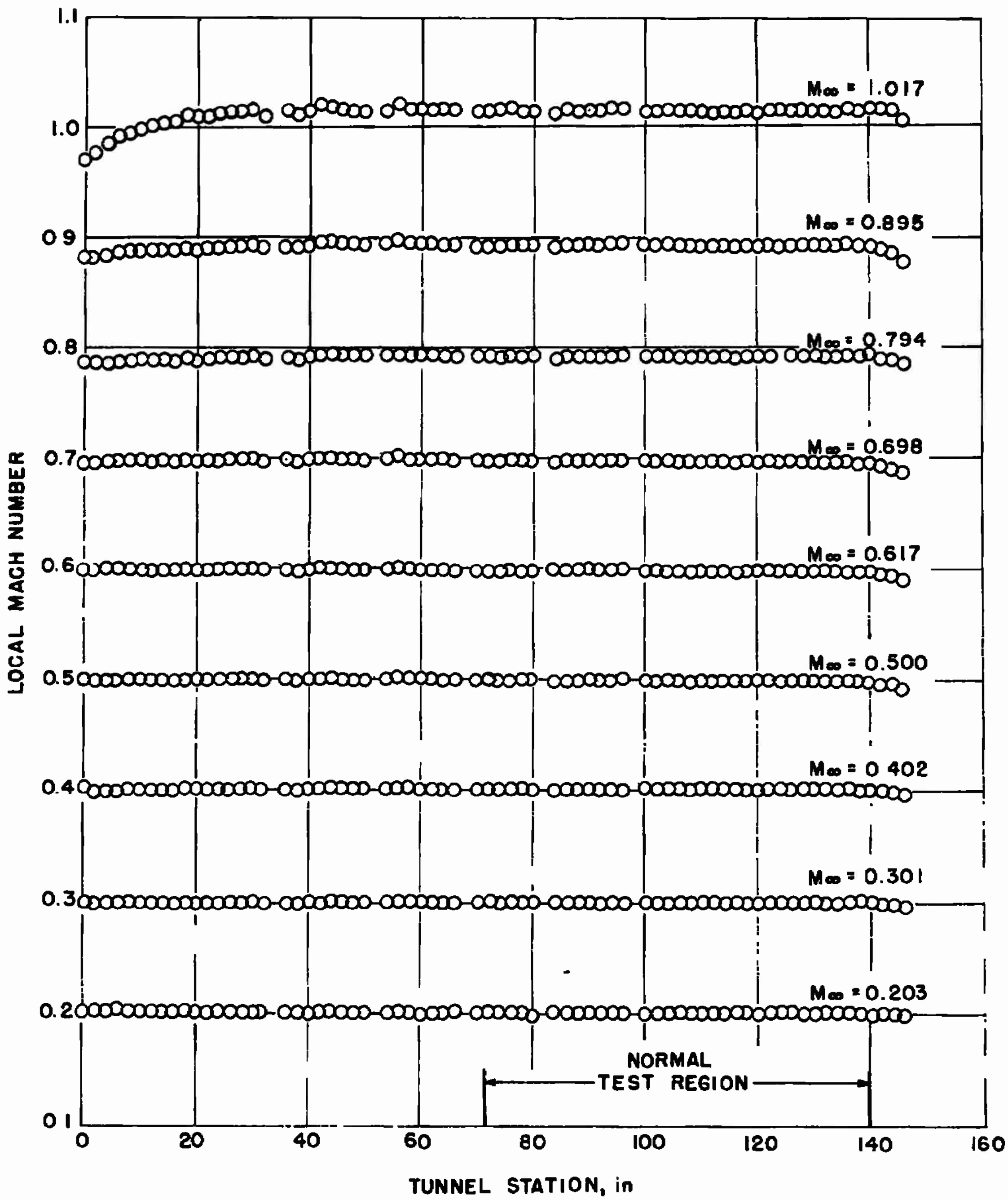
c. τ = 3 Percent
Fig. 10 Continued



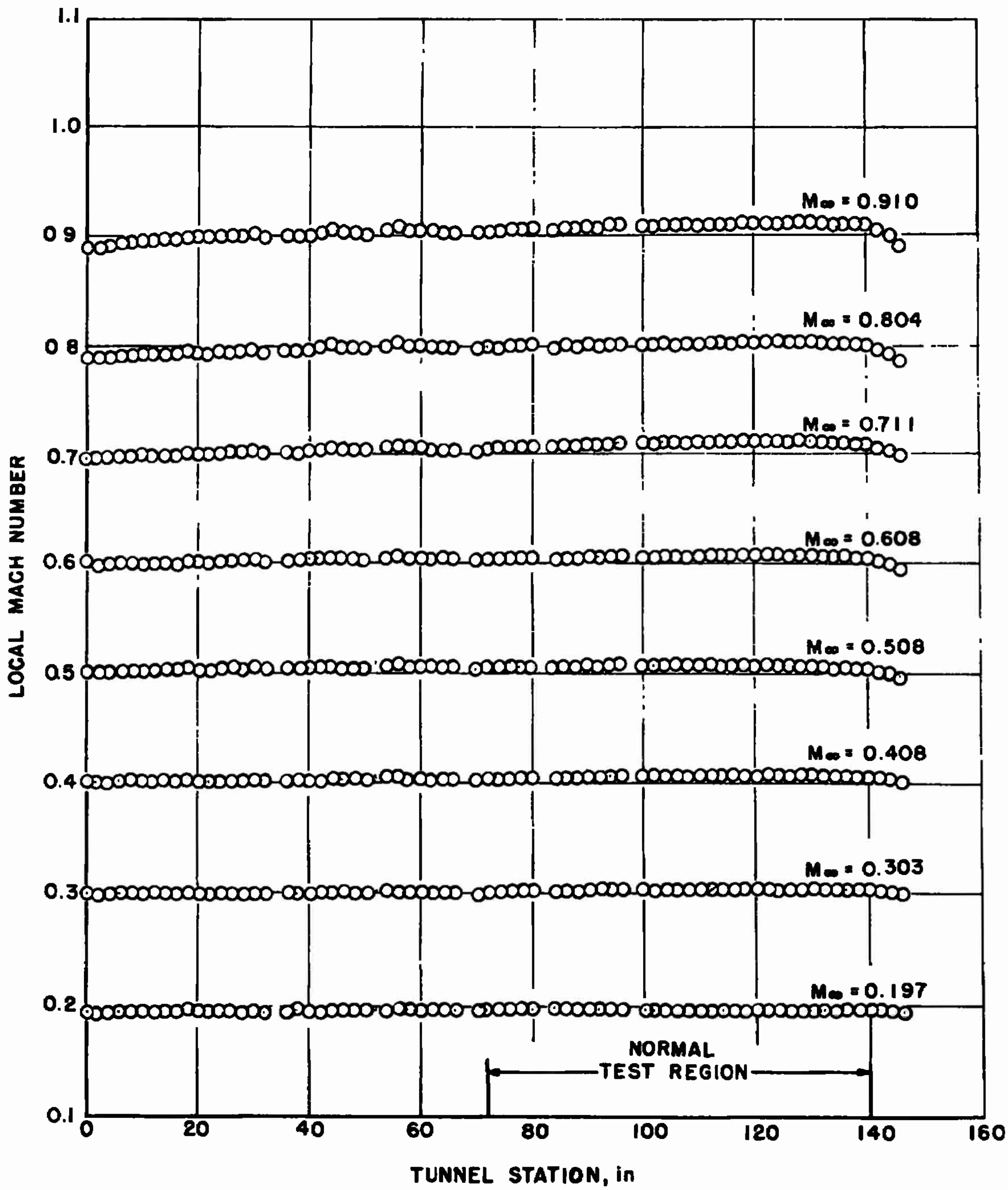
d. τ = 4 Percent
Fig. 10 Continued



e. τ = 5 Percent
Fig. 10 Continued



f. τ = 6 Percent
Fig. 10 Continued



g. τ = 8 Percent
Fig. 10 Concluded

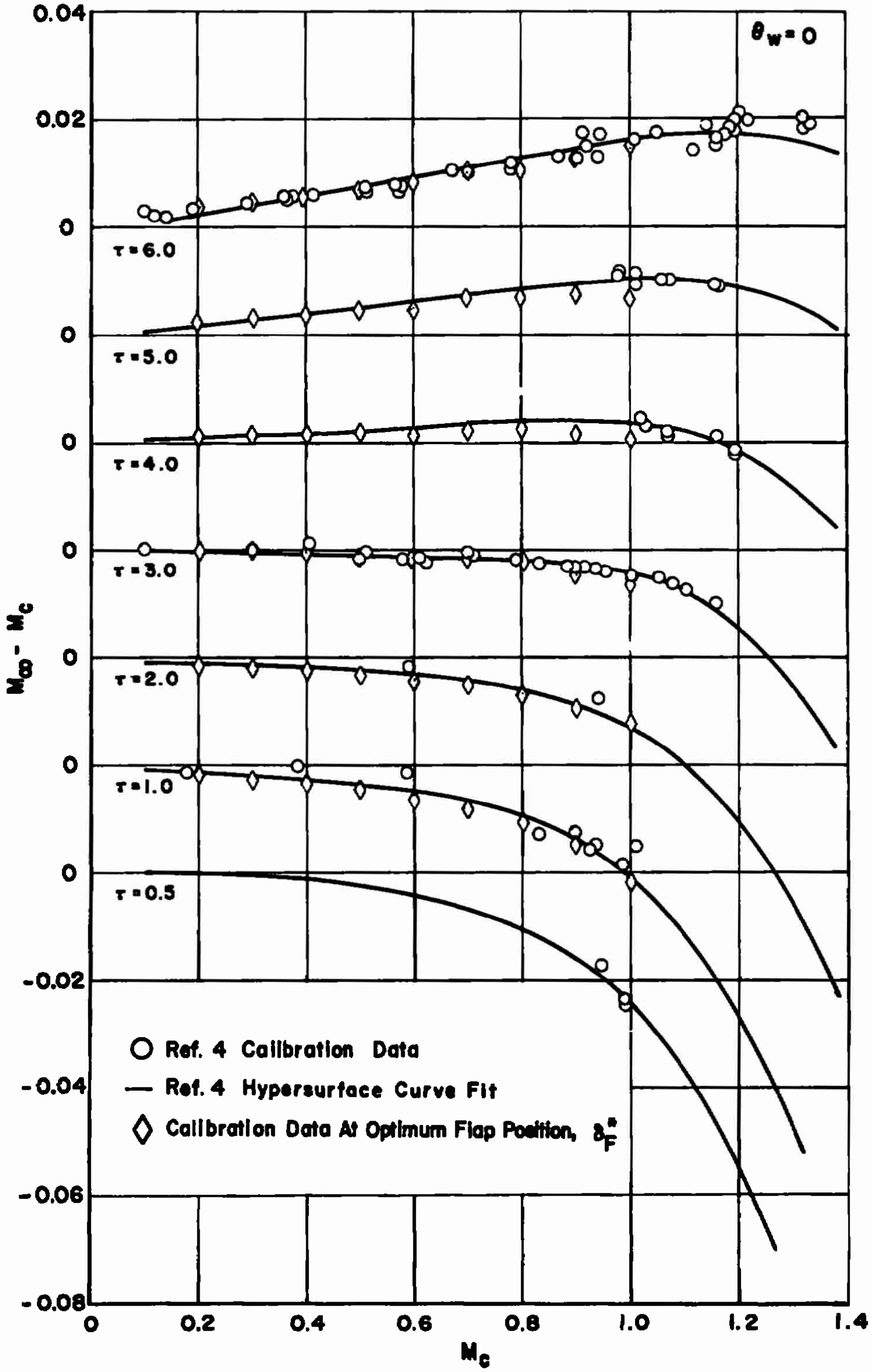


Fig. 11 Comparison of Mach Number Calibration Data for this Calibration and Ref. 4 Data

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13. ABSTRACT

Tests were conducted in the Aerodynamic Wind Tunnel, Transonic (4T) of the Propulsion Wind Tunnel Facility to determine the effectiveness of ejector flaps for plenum pumping. During the test, the Mach number was varied from 0.2 to 1.0, and the wall porosity was varied from 1.0 to 8.0 percent. The maximum Mach number attained when using flap plenum suction alone was slightly higher than 1.0. Choking which occurred at the flap hinge point prevented the attainment of higher Mach numbers. It was found that at each Mach number and porosity, a specific flap position will give a minimum centerline Mach number deviation, but for ease of operation, it is recommended that a flap position of 2.00 in. be set for all normal test conditions. The ejector flaps simplify the Tunnel 4T operation by reducing the number of control variables needed to set test conditions and also reduce the Tunnel 4T power requirements at some test conditions by as much as 19 percent.

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